Localization cues of sound sources in the upper hemisphere

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The results of two localization tests of sound sources support our hypothesis that if a direction of a sound source in the upper hemisphere is expressed by two angles \( \alpha \) and \( \beta \), instead of the azimuth angle \( \theta \) and the elevation angle \( \varphi \), the localization accuracy can be explained by two mutually independent cues. One is a binaural disparity cue which determines the angle \( \alpha \), and the other is a spectral cue which determines the angle \( \beta \). The angle \( \alpha \) is the angle between the aural axis and a straight line connecting a sound source with the center of a subject’s head. The angle \( \beta \) is the angle between the horizontal plane and the perpendicular from a sound source to the aural axis. The data indicate that the “directional band” shown by Blauert can occur in any plane parallel to the median plane.

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1. INTRODUCTION

Most former investigations have concentrated on independent evaluations of horizontal and median plane localization abilities, and few have dealt with every point in the upper hemisphere. The most notable exception is the work of Gatehouse (et al.)[1-3] with normals, monaurals, and the bilaterally hard-of-hearing, which has dealt with simultaneous identification of source’s azimuth and elevation from positions all around the subject. There has been another exception that Wallach[4] looked at the role of head movements in localization.

The present investigators have attempted to apply “new” coordinate system that is expressed by two angles \( \alpha \) and \( \beta \) instead of the more usual independent azimuth \( \varphi \) and elevation \( \theta \) angles as shown in Fig. 1, in order to explain binaural localization in the upper hemisphere via two mutually independent cues. The first is the binaural disparity cue which determines the angle \( \alpha \), and the second is the spectral cue which determines the angle \( \beta \). The former \((\alpha)\) which is the angle between the aural axis and a straight line connecting a sound source \((S)\) with the center of a subject’s head, has previously been called the lateral angle by Wallach. The latter \((\beta)\) is the angle formed by the angle between the horizontal plane and the perpendicular from a source to the aural axis which we term the “rising angle” in order to distinguish it from the usual elevation angle \((\varphi)\).

The results of several investigations appear to give at least some support to the use of our new approach to isolate the disparity and spectral cues. For example, it is well known that the azimuth angle for a source in the frontal half of the horizontal plane is determined via binaural disparity cues. Nakabayashi[5] demonstrated that unless high frequency components \((>8 \text{ kHz})\) are included in stimuli from positions in the left half of the horizontal plane, subjects experience back-front confusions with respect to the aural axis. Likewise, Roffler and
Butler\textsuperscript{6} noted the need for components above 7 kHz and Blauert\textsuperscript{7} noted 1/3 octave band noise with center frequency of 8 kHz contains the "above" information in median plane localization. Additionally, Butler\textsuperscript{8} and Gardner\textsuperscript{9} suggested that two ears are necessary, and Searle \textit{et al.}\textsuperscript{10} inferred that binaural disparity cues are necessary for accurate median plane localization. However, Hebrank and Wright,\textsuperscript{11,12} and Hebrank\textsuperscript{13} insisted that median plane localization could be done monaurally via pinna-created spectral cues. This latter view, that binaural disparities alone cannot account for accurate median plane localization but monaural cues can, is also supported by the work of Morimoto and Nomachi\textsuperscript{14}, and by Gatehouse \textit{et al.} (op cit) studies. The roles of both head movements and visual input in localization, although not precisely determined, might from some standpoints be considered to be secondary. This view is in part supported by the Gatehouse and Cox\textsuperscript{1} data, but the interaction of vision and head movements seems to be considerably more complex. Finally, Morimoto and Ando\textsuperscript{15} have shown that if head-related transfer functions are accurately and completely simulated accurate horizontal and median plane localizations can be attained without any consideration or involvement of either head movements or visual input.

In summary, it is not clear whether most of these foregoing results (with the exception of Gatehouse \textit{et al.}) can directly apply to our present hypothesis since they were based on single horizontal and median plane measurements, and under the assumption that the perceived images appeared exclusively on those single planes. Therefore, we conducted tests where subjects were required to place their perceived images in both azimuth and elevation simultaneously.

2. \textbf{LOCALIZATION TEST I}

2.1 Method

2.1.1 Subject

Subjects were four males, 22 years of age $\pm$ 1 year, with normal hearing sensitivity.

2.1.2 Apparatus

Seven cylindrical loudspeakers (diameter: 108 mm, length: 350 mm) were located at every 15 degrees in the right quadrant of the traverse plane on the upper hemisphere as shown in Fig. 2. The speaker radius was 1.5 m relative to the center of the subject's head. The frequency characteristics of the seven loudspeakers were flattened within $\pm$ 3 dB in the frequency range of the stimulus by a frequency equalizer.

The stimuli were three kinds of band limited white noise conditions: (1) a wide-band (300–13,600 Hz); (2) a high-pass (4,800–13,600 Hz) and (3) a low-pass (300–4,800 Hz). All stimuli were shaped by a passive filter (60 dB/oct) which was connected between an interval timer with abrupt rise-fall time and an amplifier to the loudspeakers. They were delivered at 50 dB(A) SPL for one second, followed by an interval of eleven seconds, and repeated six times for each direction, in a random order.

2.1.3 Procedure

Each subject was individually tested while seated, head fixed, in a partially darkened anechoic chamber. Forty-two recording sheets with a circle and two arrows on it were supplied. An arrow on the top of Fig. 2 Arrangement of sound sources in the first test.
the circle indicates the 0° azimuth angle \( \psi \), and one on the right of the circle indicates the 0° elevation angle \( \theta \). The subject's task was to mark down what he believed to be the azimuth angle \( \psi \) and the elevation angle \( \theta \) of a sound image for each one second stimulus presentation. If the sound image was perceived to be overhead, a cross was penned in at the center of the circle. The eleven second inter-stimulus interval allowed the subject to take up the next record sheet. The only light in the chamber was placed such that it provided just enough illumination for the subject to see and utilize the record sheets.

The subjects were tested with each band limited noise separately. Thus each subject made a total of 126 judgements for the entire task.

2.2 Results

Responses to the first stimulus from each source direction were regarded as a practice trial and they were excluded from the results. The azimuth angle \( \psi \) and the elevation angle \( \theta \) marked by the subjects were read with a protractor to an accuracy of one degree and transformed to the proposal lateral angle \( \alpha \) and the rising angle \( \beta \) coordinates by Eq. (1).

\[
\begin{align*}
\cos \alpha &= \sin \psi \cos \theta \\
\sin \beta &= \sin \theta/(\sin^2 \theta + \cos^2 \psi \cos^2 \theta)^{1/2}
\end{align*}
\]  (1)

Table 1 shows the localization errors \( E \) as already published by Morimoto and Ando\(^{15}\) for the angle \( \alpha \) and the angle \( \beta \) separately. An error is defined as the average of the absolute deviations of the perceived from the "true" source direction. The error

Fig. 3 Perceived directions of all four subjects for the wide-band noise in the traverse plane (represented on the \( \alpha-\beta \) plane).
of the angle $\alpha$ is very small for any stimulus as are the errors of the angle $\beta$ for the wide-band and the high-pass noises. But, the $\beta$ error for the low-pass noise is very large.

Figures 3, 4 and 5 show perceived directions of all four subjects represented on the $\alpha$-$\beta$ plane in order to discuss their detailed behaviors. The diameter of the circle is proportional to the number of responses within each range of five degrees. In each figure, the intersection of the two solid lines indicates the source direction. But, the just transverse direction is indicated at an intersection of the angle $\alpha=0^\circ$ and the angle $\beta=90^\circ$ for convenience, though the direction is defined by only the angle $\alpha$ ($=0^\circ$).

Figure 3 shows the results of the test in which the wide-band noises were presented to subjects. For any source direction, perceived directions almost agree with the source direction. That is, both the lateral angle $\alpha$ and the rising angle $\beta$ are perceived correctly. Figure 4 shows the results of the test in which the high-pass noises are presented. Again, all perceived directions agree with the source direction. Figure 5 shows the comparable data for the low-
pass noises. Unlike the wide-band and high-pass data perceived direction does not agree with the source direction, except when stimuli are presented from the sound source at the just transverse direction defined by only the angle $\alpha=0^\circ$ (Fig. 5 (a)). Now, if the two coordinates are separated, we can see that the angle $\alpha$ is perceived correctly for all source directions although at angles $\alpha=60^\circ$ and $75^\circ$ there is a slight shift towards $\alpha=0^\circ$. However, any angle $\beta$ is perceived far from $\beta=90^\circ$. That is, most sound images do not appear in the traverse plane, but shift towards the horizontal plane ($\beta=0^\circ$ or $180^\circ$). In other words, sound images for the low-pass noise condition appear closer to the horizontal plane within the plane defined by the angle $\alpha$ of a sound source which is parallel to the median plane.

Figure 6 shows the perceived directions of all four subjects for the low-pass noises using the more common $\theta-\psi$ coordinates for reference. In comparison with Fig. 5, we see that neither the azimuth angle $\psi$ or the elevation angle $\theta$ are perceived correctly, except when stimuli are presented from the sound source at the just transverse direction (Fig. 6 (a)).

3. LOCALIZATION TEST II

The purpose of this test was not only to verify our hypothesis and previous data but to confirm whether the “directional band” of Blauert occurs in any plane defined by the lateral angle $\alpha$, which is parallel to the median plane.

3.1 Method
3.1.1 Subject
Subjects were four males, 22 years of age $\pm 1$
year, with normal hearing sensitivity. Three of them were the same males as used for the first test.

3.1.2 Apparatus

Nine loudspeakers which have the same shape as used for the first test were located at the positions defined by combining one of three lateral angles $\alpha = 30^\circ$, $60^\circ$ and $90^\circ$ with one of three rising angles $\beta = 0^\circ$, $90^\circ$ and $180^\circ$ on the right quadrant of the upper hemisphere as shown in Fig. 7. The radius of the sphere was 1.5 m. The frequency characteristics of the nine loudspeakers were flattened within $\pm 3$ dB in the frequency range of the stimulus by a frequency equalizer.

Stimuli were six 1/3 octave band noises filtered by an active filter (48 dB/oct), with center frequencies of 1.0, 3.15, 5.0, 6.3, 8.0 and 10.0 kHz, respectively. According to Blauert, 1.0 kHz and 10.0 kHz are the directional "rear" bands, while 3.15 kHz and 5.0 kHz are the directional "front" bands, and 8.0 kHz is the directional "above" band.

3.1.3 Procedure

The stimulus was delivered at 50 dB(A) SPL for one second with abrupt rise-fall time, followed by an interval of five seconds. In one test block, fifty-four different stimuli (nine source directions and six center frequencies) were presented once in a random order. The subject was tested separately on six blocks of trials, in which orders of the presentation of stimuli were different. All other test procedures were the same as in the first test.

3.2 Results

All responses to the first block of trials were excluded from the results, and thus the data represent

![Fig. 6 Perceived directions of all four subjects for the low-pass noise in the traverse plane (represented on the $\theta$-$\psi$ plane).]
only the trials from the last five blocks.

Table 2 shows averaged values and standard deviations of perceived lateral angle \( \alpha \), independent of source rising angle \( \beta \). The perceived angle \( \alpha \) of any stimulus agree relatively well with the "true" source angle \( \alpha \). Most of the differences that were found were less than ten degrees, except the value for 1/3 oct. band noise with the center frequency of 10.0 kHz at the source angle \( \alpha = 60^\circ \). Likewise, the standard deviations for any stimulus is under fourteen degrees. It is the smallest at the source angle \( \alpha = 90^\circ \), and the smaller the angle \( \alpha \) becomes, the larger it becomes, except for 1/3 oct. band noise with the center frequency of 10.0 kHz. On the whole there is a tendency for our data to comply with Mills' observation that the minimum audible angle becomes larger as source direction changes from the front to the lateral direction in the horizontal plane.

As previously indicated perceived angle \( \beta \) is divided into three sections, "front," "above" and "rear" in Blauert. In order to compare our findings with his data, Figs. 8 (a), (b) and (c) respectively show the relative frequencies of "front," "above" and "rear" judgements, as a function of the center frequency of 1/3 oct. band noise. Although no judgements of our subjects show such remarkable directional bands, as indicated in Blauert, the banding that does occur for each judgement is recognizable as being at the same center frequency as his paper indicated. Furthermore, the "patterns" of the relative frequencies of each judgement as a function of the center frequency are similar to each other within the three planes defined by three angles \( \alpha \), and are also similar to Blauert's. Table 3 shows the degree of the similarity of the "pattern" in each judgement by the use of the correlation coefficient. Most values in the table show high correlation.

### 4. DISCUSSION

Binaural disparity cues are not influenced by the frequency range of a stimulus, because it is well known that interaural amplitude differences are effective cues for high frequency localization while interaural phase differences are for the low frequencies. Accordingly, it can be considered from the results of both of our tests, that the lateral angle \( \alpha \) of a sound source is determined by binaural disparity cues regardless of the frequency range of the stimulus.

In opposition to this, spectral cues are considerably influenced by the particular frequency range of the stimulus. Spectral cues have been discussed mainly to explain the median plane localization. Several phenomena which explain that spectral cues determine the elevation of a sound source in the median plane have been reported. One of them is the phenomenon that unless high frequency components (> 5 kHz) are included in stimuli from above

<table>
<thead>
<tr>
<th>Source angle ( \alpha )</th>
<th>Center frequency of 1/3 oct. band noise (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>30° Av.</td>
<td>28</td>
</tr>
<tr>
<td>SD</td>
<td>11</td>
</tr>
<tr>
<td>60° Av.</td>
<td>52</td>
</tr>
<tr>
<td>SD</td>
<td>9</td>
</tr>
<tr>
<td>90° Av.</td>
<td>89</td>
</tr>
<tr>
<td>SD</td>
<td>4</td>
</tr>
</tbody>
</table>
in the median plane, sound images are not perceived at the above, but at the front or the rear in the median plane (Hebrank and Wright and Morimoto). Another of them is the phenomenon that the stimulus which consists of 1/3 oct. band noise is localized at a certain biased direction in the median plane corresponding to its center frequency (Blauert).

With these phenomena as background, we conducted two localization tests in this paper. In our first test, the rising angle $\beta$ of the wide-band and the high-pass noises were accurately localized. However, the angle $\beta$ of the low-pass noise was not and most of the responses to it were shifted to the front or the rear along the horizontal plane. These results coincide with those of Hebrank and Wright, and Morimoto. In our second test, the angle $\beta$ of the 1/3 oct. band noise was perceived at a certain biased angle which corresponded to its center frequency in the same manner as Blauert. Accordingly, it can be considered that the rising angle $\beta$ of a sound source is determined by spectral cues.

Furthermore, the findings that the $\alpha$ coordinates of both the low-pass and 1/3 oct. band noises are perceived correctly, although their $\beta$ coordinates are not, means that the angle $\alpha$ and the angle $\beta$ are determined independently from each other.

In the second experiment, directional bands did not occur so remarkably as in Blauert. It is possible that our different methodologies and numbers of subjects, might account for this difference. But, the directional bands for each judgement were found at the same center frequencies as shown by Blauert and the “patterns” of the relative frequency of each judgement in the three planes defined by the angle $\alpha$ were similar to each other, and to his. Thus it seems reasonable to suggest that the spectral cues which determine the angle $\beta$ play the same role in any plane defined by the angle $\alpha$, which is parallel to the median plane.

![Fig. 8](image-url)

**Table 3** Correlation coefficient between “patterns” of relative frequencies of “front,” “above” and “rear” judgements. The 90°, 60° and 30° indicate the “patterns” in the planes defined by the angle $\alpha=90^\circ$, 60° and 30°, respectively. B indicates Blauert’s.

<table>
<thead>
<tr>
<th>Judgement</th>
<th>Front</th>
<th>Above</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-90°</td>
<td>.81</td>
<td>.89</td>
<td>.86</td>
</tr>
<tr>
<td>B-60°</td>
<td>.96</td>
<td>.92</td>
<td>.79</td>
</tr>
<tr>
<td>B-30°</td>
<td>.91</td>
<td>.75</td>
<td>.92</td>
</tr>
<tr>
<td>90°-60°</td>
<td>.95</td>
<td>.96</td>
<td>.95</td>
</tr>
<tr>
<td>90°-30°</td>
<td>.82</td>
<td>.76</td>
<td>.87</td>
</tr>
<tr>
<td>60°-30°</td>
<td>.81</td>
<td>.82</td>
<td>.81</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

The results of two localization tests suggest that:
(1) the lateral angle $\alpha$ and the rising angle $\beta$ as defined here can better explain binaural sound localization in upper hemisphere than the more usually used azimuth and the elevation angles; (2) the lateral angle $\alpha$ is determined by binaural disparity cues; (3) the rising angle $\beta$ is determined by spectral cues; and, (4) the two angles are determined independently of each other. Consequently, they support our hypothesis about how localization in the upper hemisphere is accomplished. Furthermore, it is clear that the same “directional band” as delineated by Blauert occurs in any plane which is parallel to the median plane.

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